

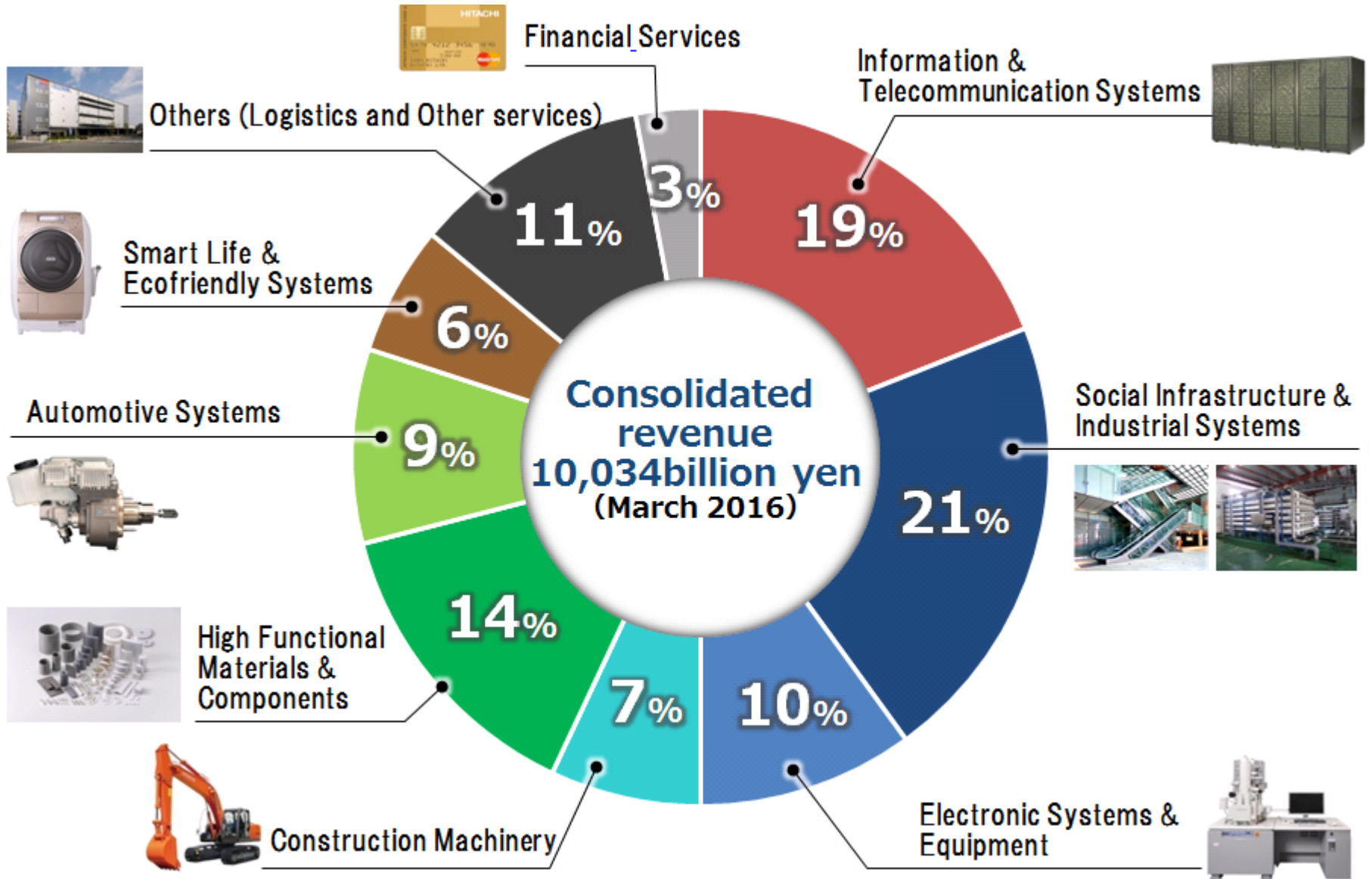
October 9-11, Aachen

High Accuracy Range Sensing System Based on FMCW

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Phillip Sandborn, Ming C. Wu, University of California, Berkeley

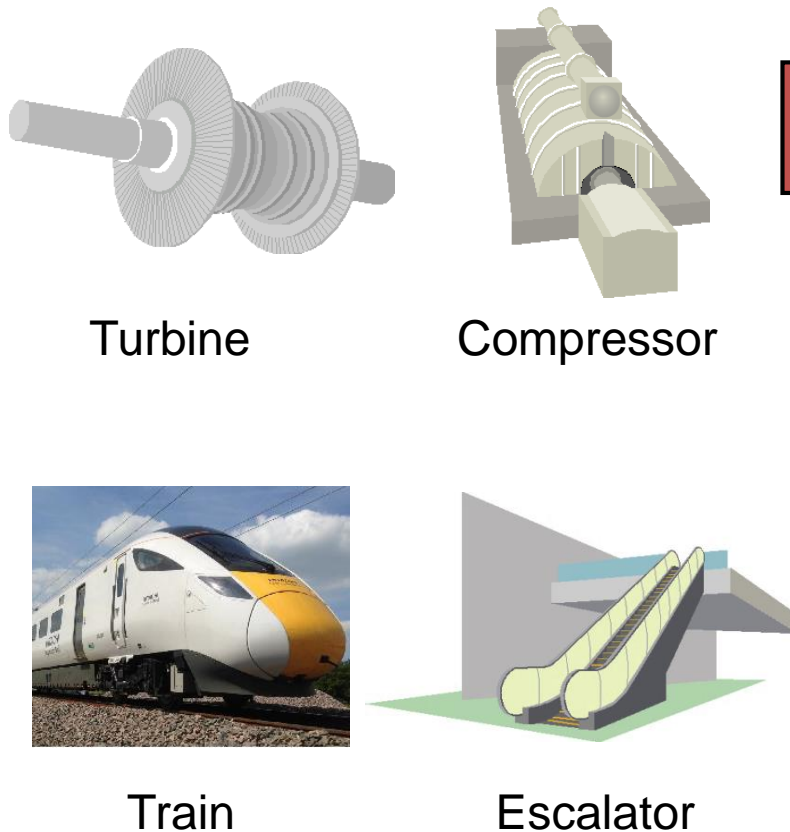


1. Company profile of Hitachi Ltd.
2. 3D Imaging Applications and Technology
3. Principle of Frequency-Modulated Continuous-Wave (FMCW)
4. Resampling Method
5. Specification of Vertical Cavity Surface Emitting Laser (VCSEL)
6. Evaluation of Distance Measurement
7. 3D Imaging Results

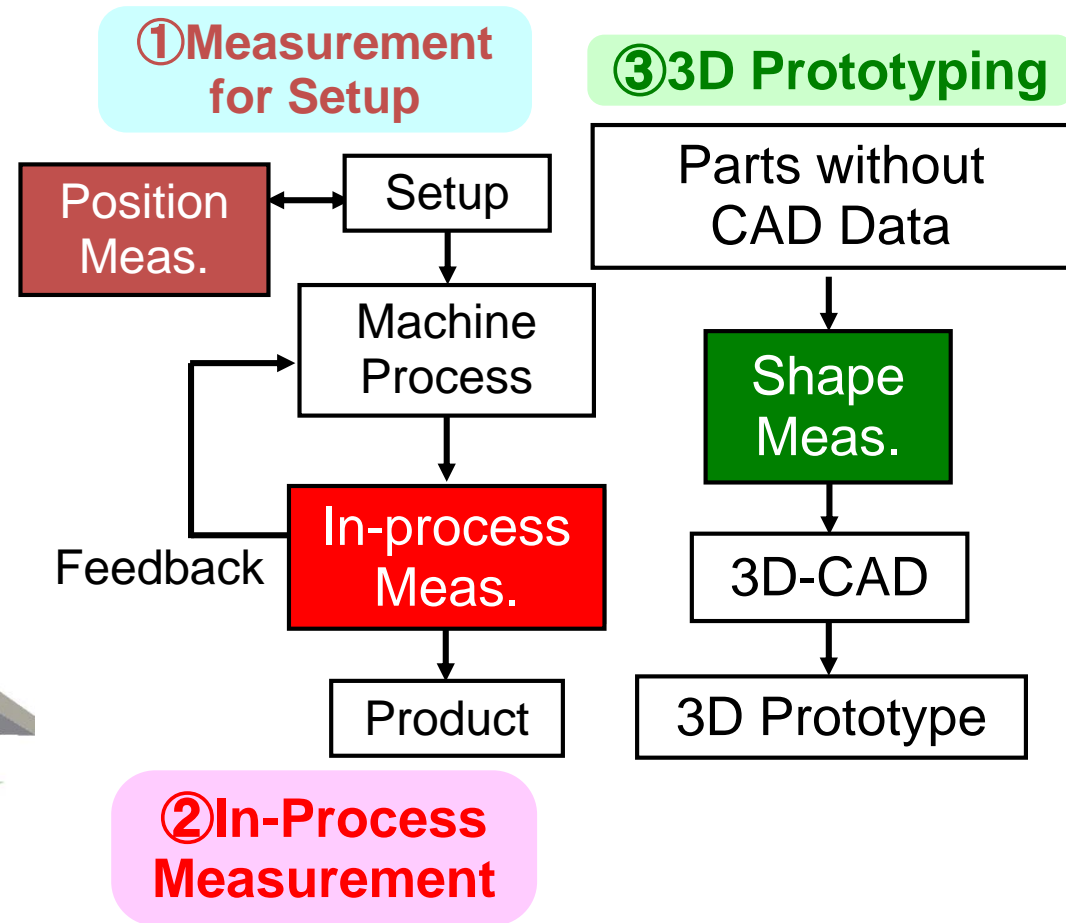


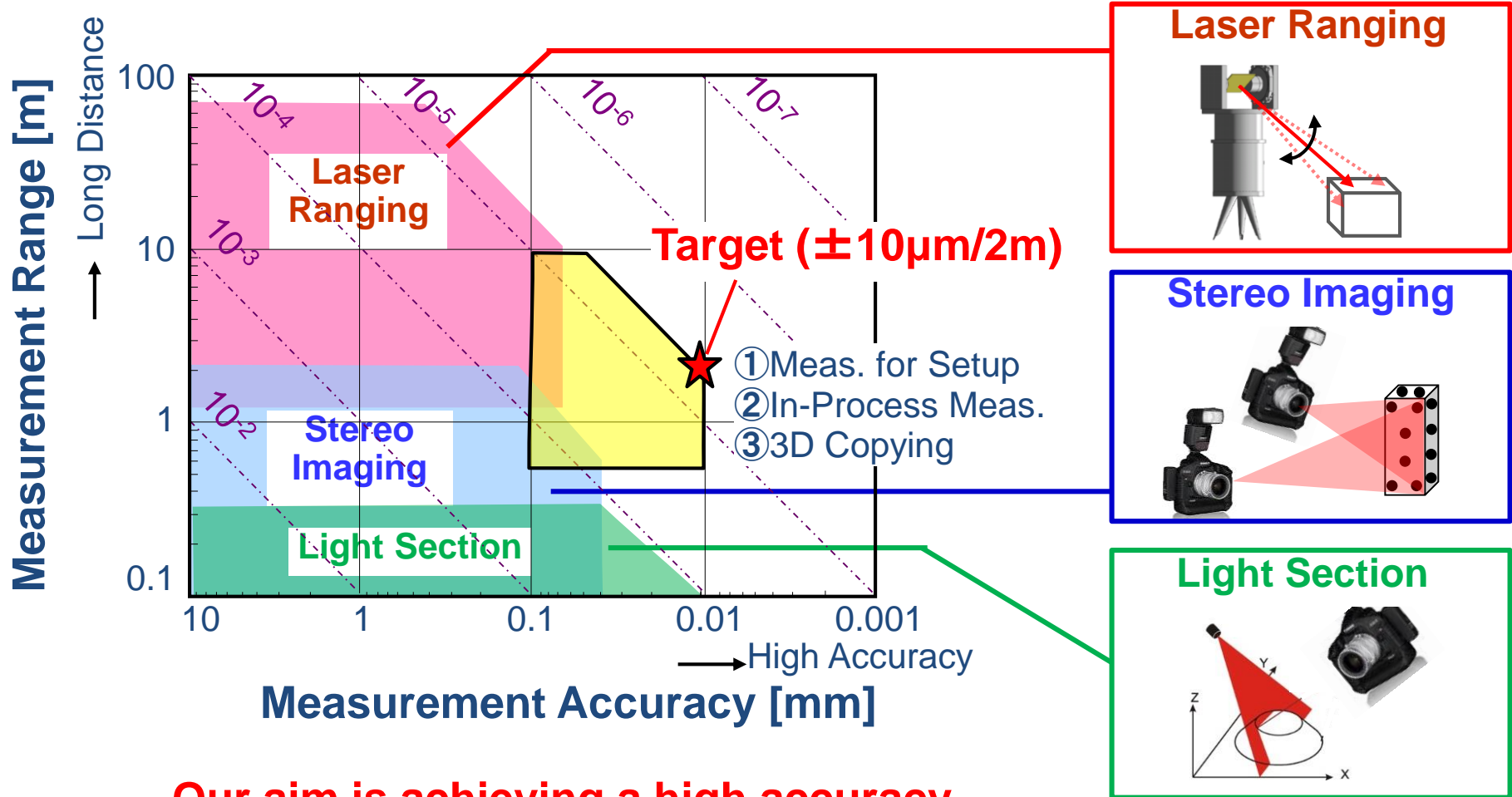
Industrial Field

Medium and Large Size Products



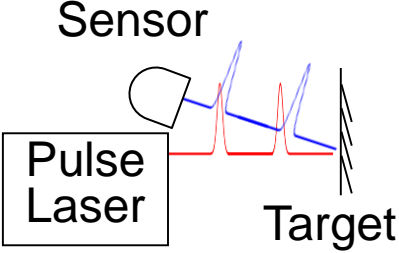
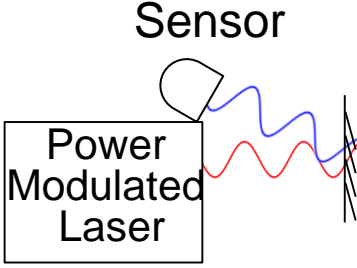
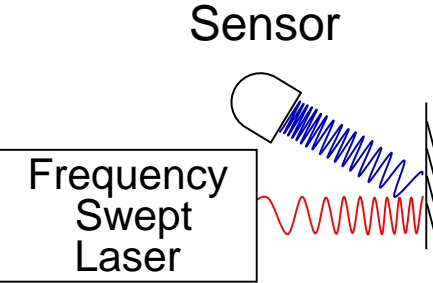
Need for High Accuracy Shape Measurement



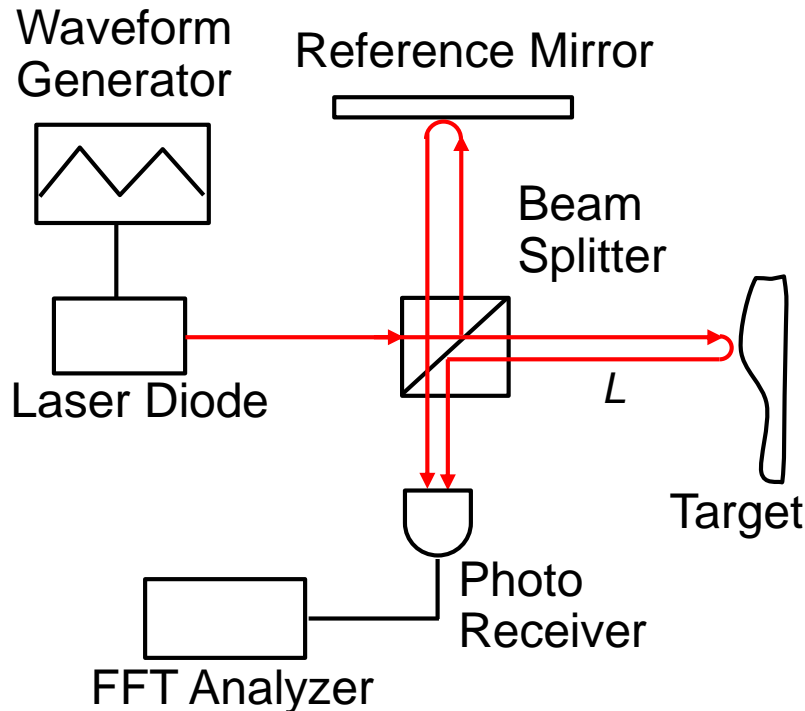


Our aim is achieving a high accuracy Measurement by enhancing laser ranging

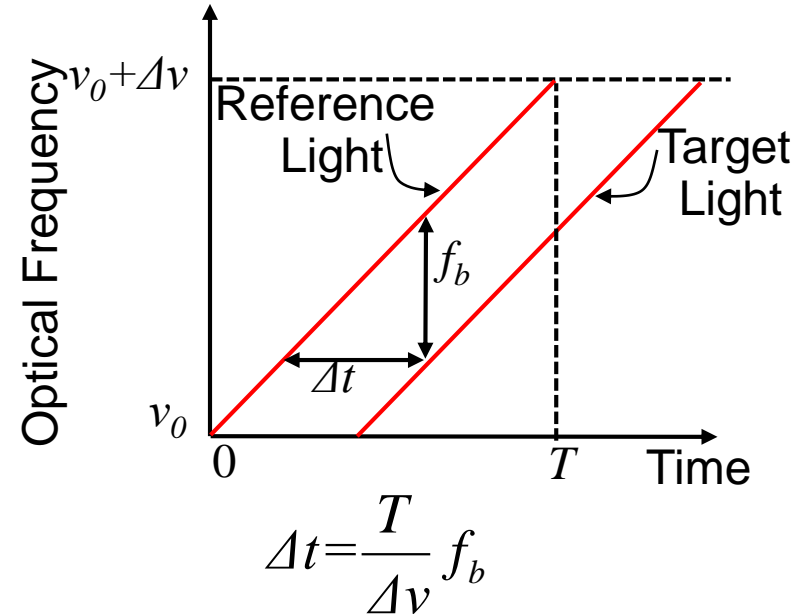
Comparison of Laser Ranging Method

Method	Time of Flight	Phase Shift	FMCW
<p>Principle</p>	 <p>Sensor</p> <p>Pulse Laser</p> <p>Target</p> <p>Time \propto Distance</p>	 <p>Sensor</p> <p>Power Modulated Laser</p> <p>Phase \propto Distance</p>	 <p>Sensor</p> <p>Frequency Swept Laser</p> <p>Frequency \propto Distance</p>
<p>Accuracy / Distance</p>	<p>$\pm 4\text{mm} / 50\text{m}$</p>	<p>$\pm 2\text{mm} / 25\text{m}$</p>	<p>$\pm 10\ \mu\text{m} / 2\text{m}$</p>

Setup



Distance Measurement Principle

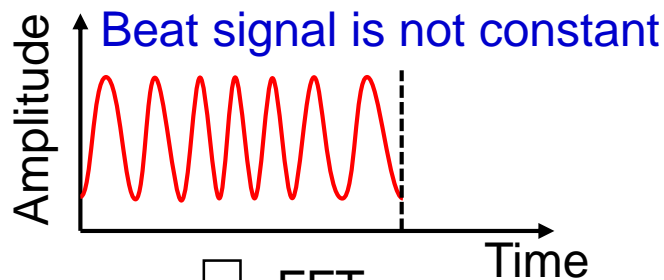
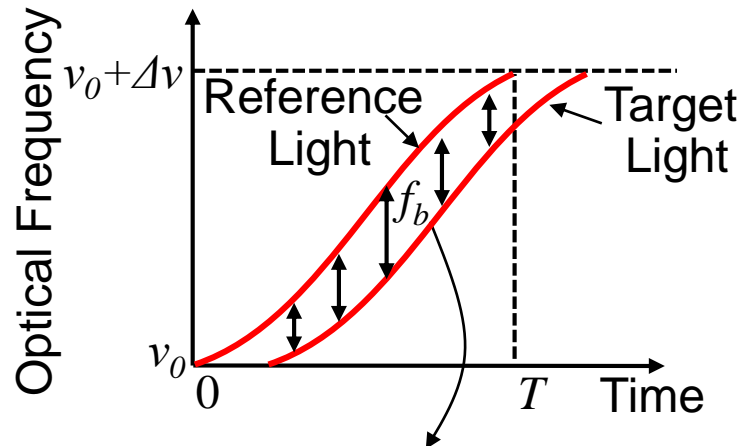


Light travels a roundtrip distance L during Δt .
 L is expressed using light speed c .

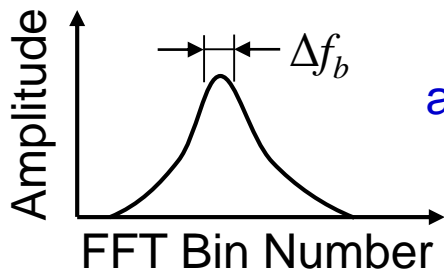
$$\underline{L} = \frac{1}{2} c \Delta t = \frac{cT}{2\Delta v} \underline{f_b} \quad \text{Distance } L \propto \text{Beat Frequency } f_b$$

Issue of FMCW

Nonlinearity of Optical Frequency Sweep



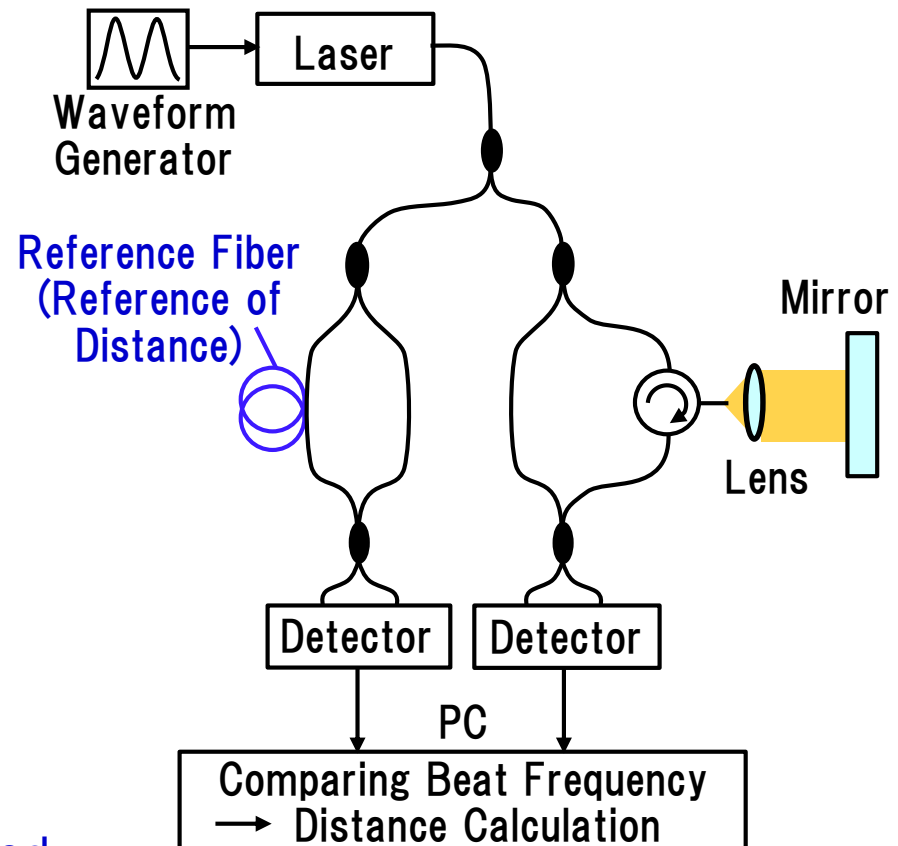
FFT



Measurement accuracy is degraded

$$\Delta L = \frac{cT}{2\Delta v} \Delta f_b$$

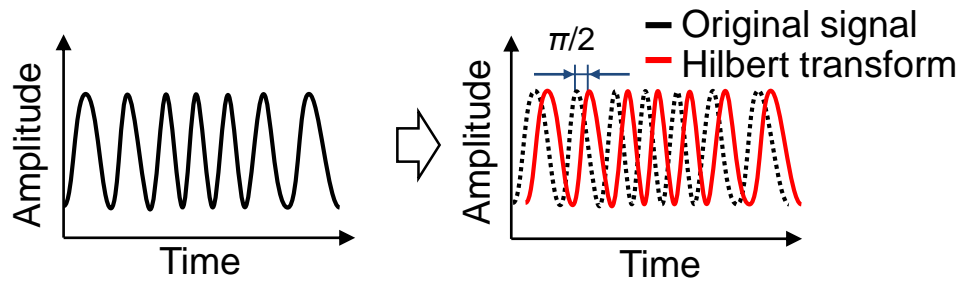
Setup for Resampling



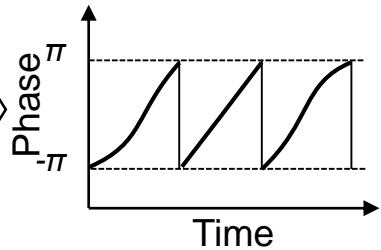
Principle of Resampling Method

Reference Beat Signal

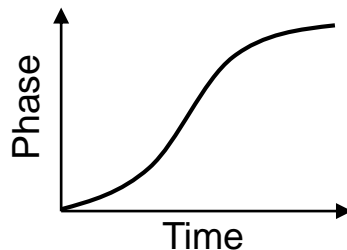
① Hilbert Transform



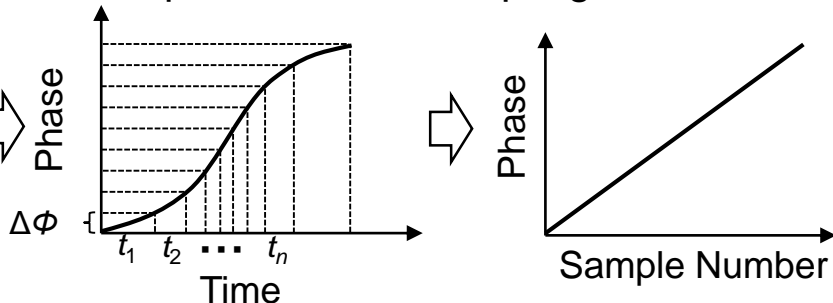
② Phase Calculation



③ Phase Unwrap

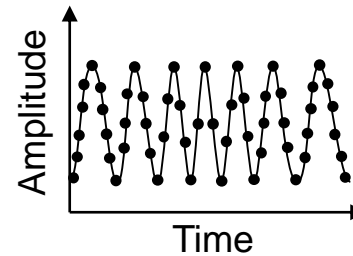


④ Interpolated New Sampling Time

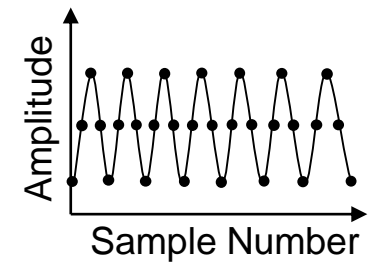


Target Beat Signal

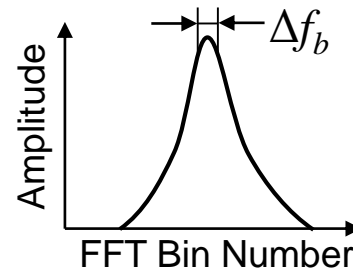
Before Re-Sampling



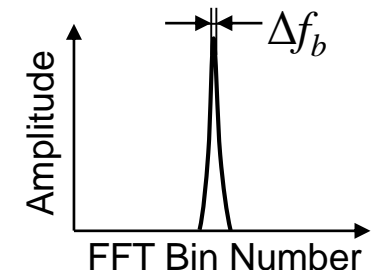
After Re-Sampling



FFT



FFT



$$\Delta L = \frac{cT}{2\Delta\nu} \Delta f_b$$













Measurement accuracy is improved after re-sampling

[Ref.] Suppression of nonlinear frequency sweep in an optical frequency-domain reflectometer by use of Hilbert transformation, Applied Optics vol.44, No.35, (2005)

$$\text{Distance Resolution } \frac{\Delta L}{\Delta \nu} = \frac{c}{2 \Delta \nu} \frac{\text{Wavelength Sweep Range}}{\Delta \nu}$$

Long swept range laser is necessary for high accuracy measurement

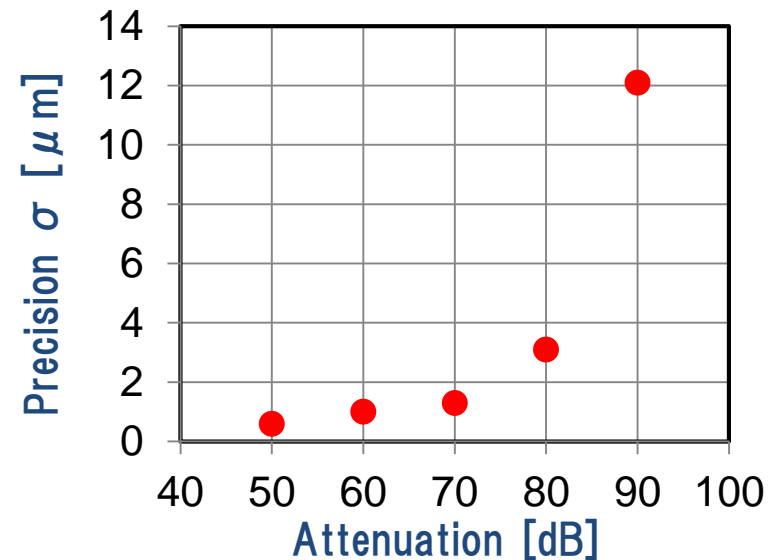
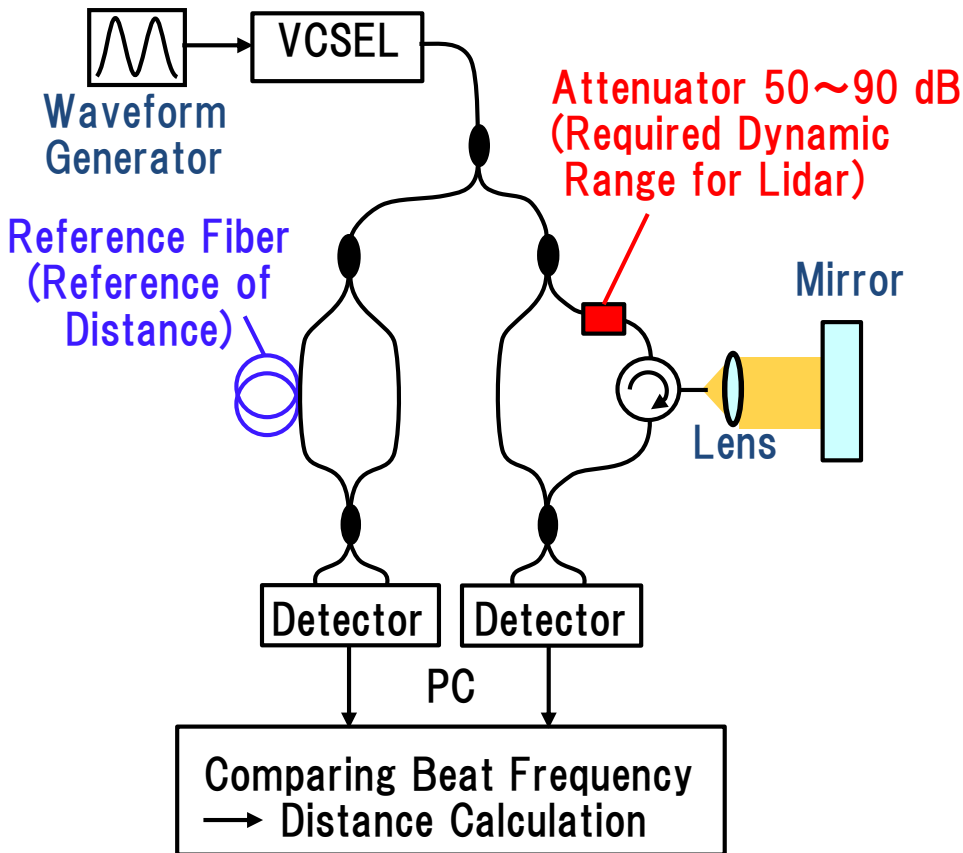
Commercial Laser

Laser Type	ECL*	MEMS-VCSEL	VCSEL
Wavelength Swept Range	 50nm	 100nm	 10nm
Measurable Distance	 100m	 0.05m	 15m
Measurable Speed	 0.04kHz	 100kHz	 30kHz
Price	 \$31,000	 \$35,000	 \$320

*ECL: External Cavity Laser

Setup

Measurement Result



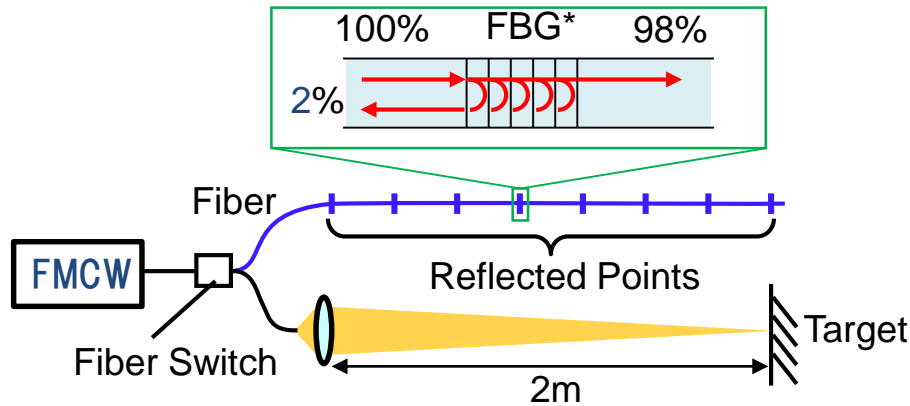
Precision was better than 10 μm @ -80 dB.
Precision was better than 1 μm @ -60 dB.

In case of near distance measurement (<1m), detected light level is higher than -60dB.

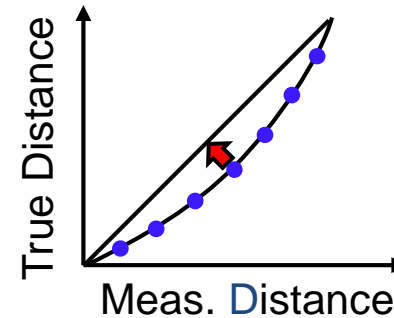
Setup

*FBG: Fiber Bragg Grating

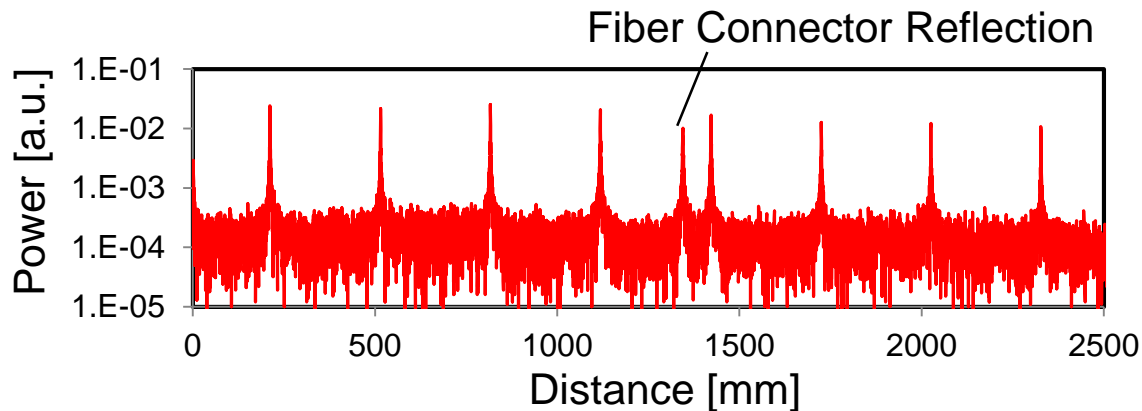
Distance Calibration Optical System



Before measuring target distance, System can calibrate distance by measuring each reflection point.

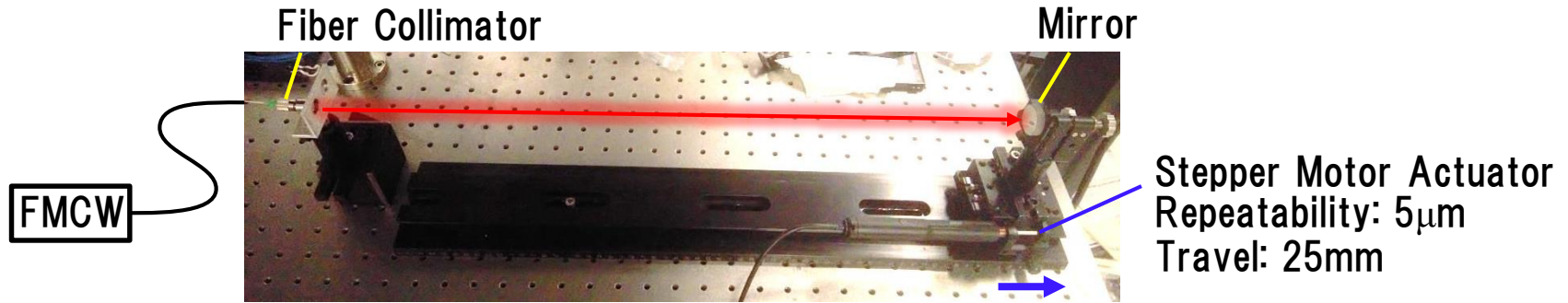


Measurement Result



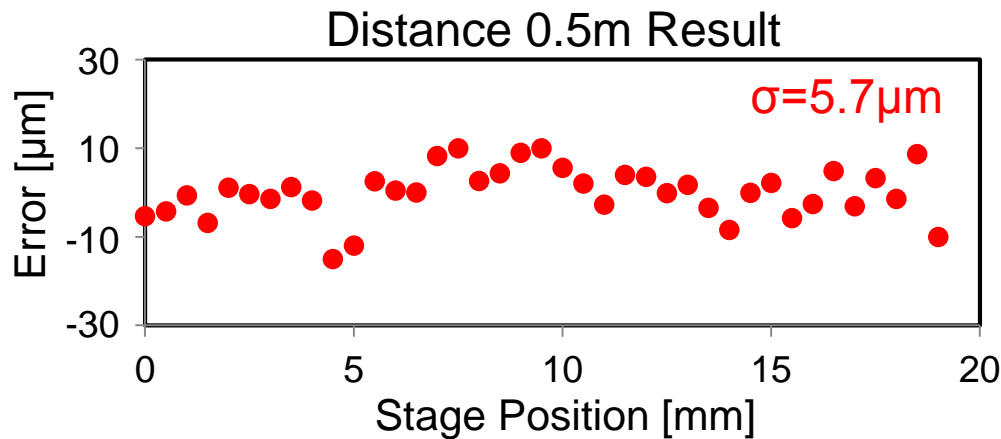
All 8 reflection points were detected simultaneously.

Setup



Targets at 0.5, 1, 1.5 and 2 meters were measured.

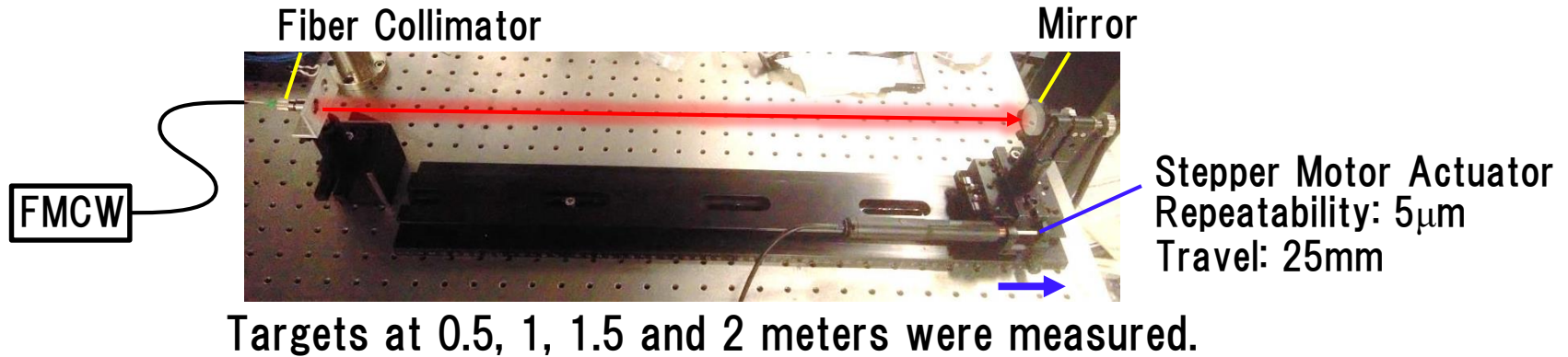
Measurement Result



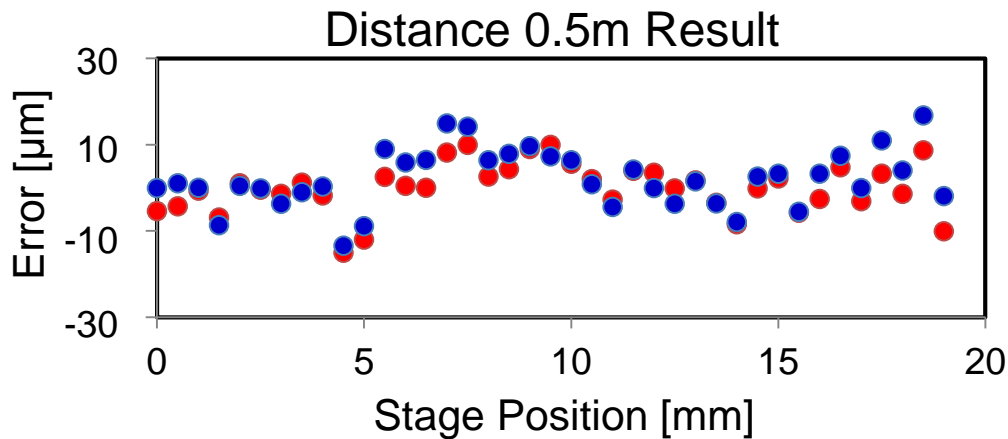
$\sigma=5.8\mu\text{m}$ at 1m
 $\sigma=5.5\mu\text{m}$ at 1.5m
 $\sigma=6.1\mu\text{m}$ at 2m

**Accuracy was better than
10 μm over 2 m.**

Setup



Measurement Result



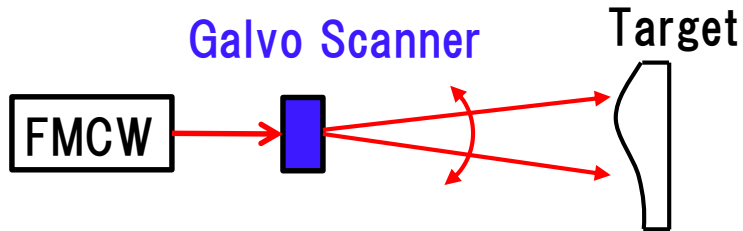
- 1st measurement
- 2nd measurement

This result contains a stage position error. In the future, I will evaluate using interferometer.

Interferometer can measure relative distance with sub micro meter accuracy.

3D Imaging - Small Size -

Setup



Target



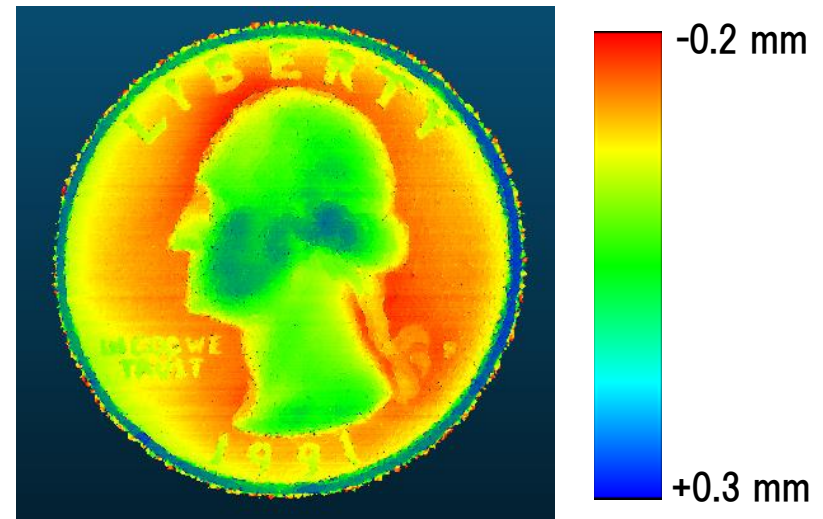
24.26 mm

Distance from scanner: 700 mm
Data points: 440 × 440 points

Measurement result 3D Rendering



Height Data



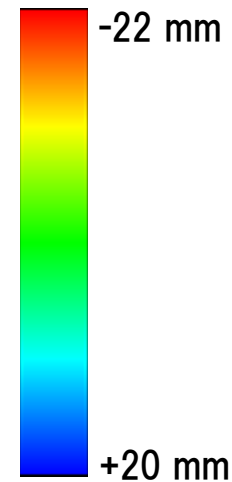
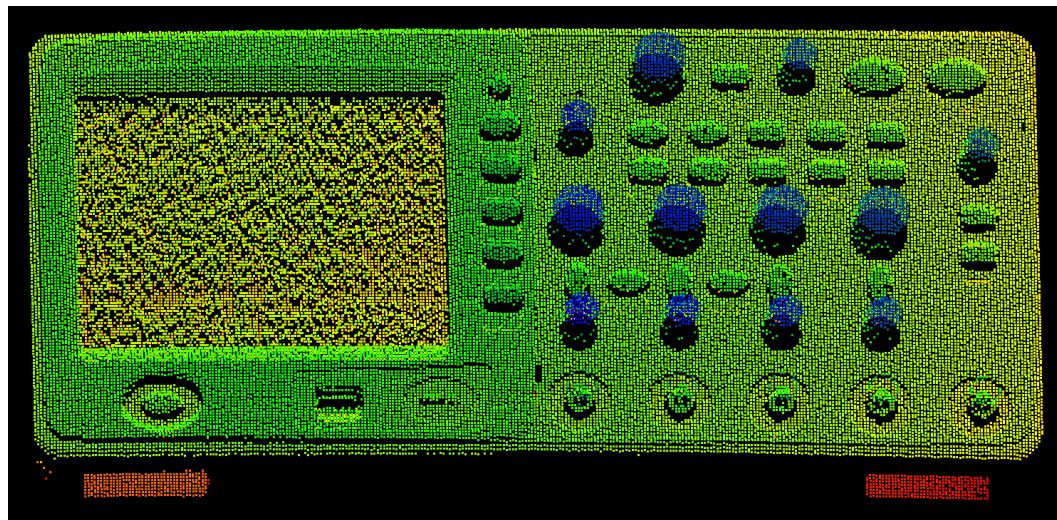
3D Imaging - Medium Size -

Target

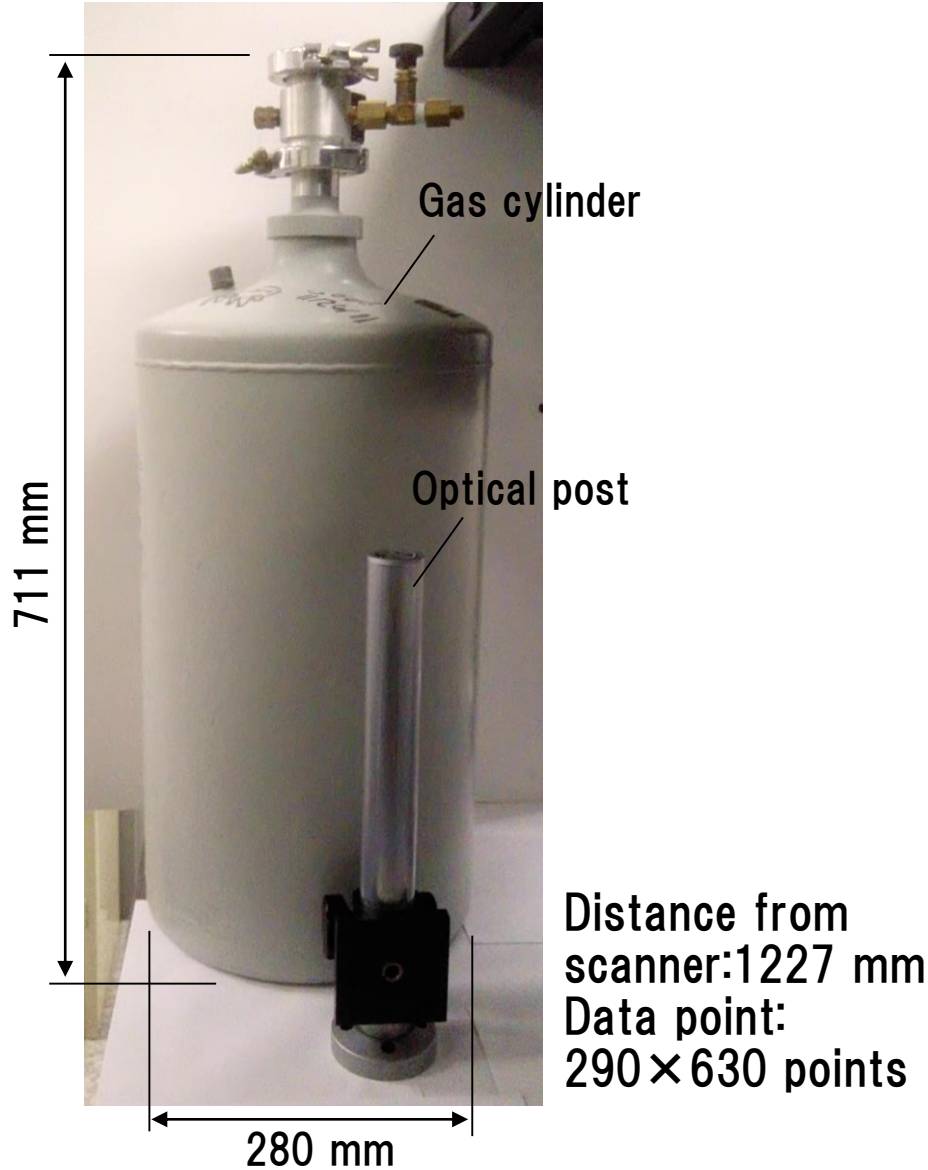


Distance from scanner: 1442 mm
Data points: 172 × 361 points

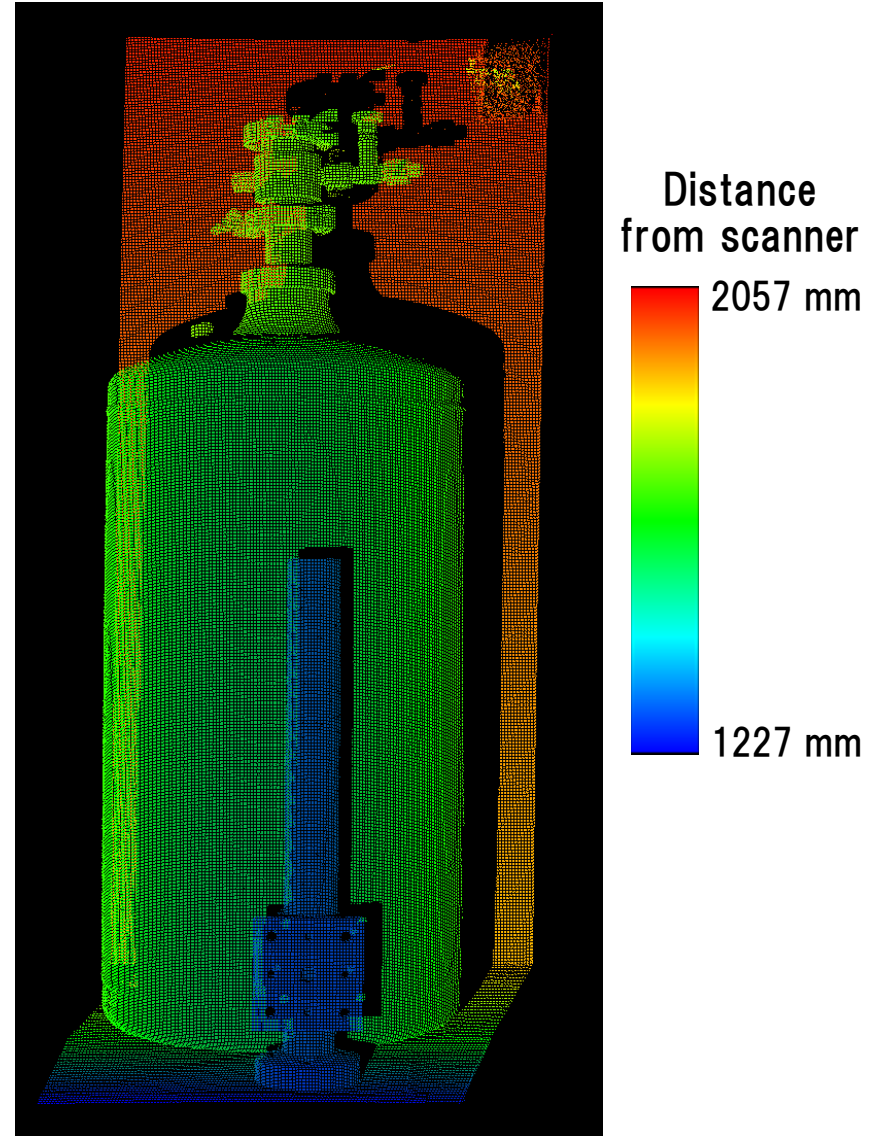
Measurement result



■ Target

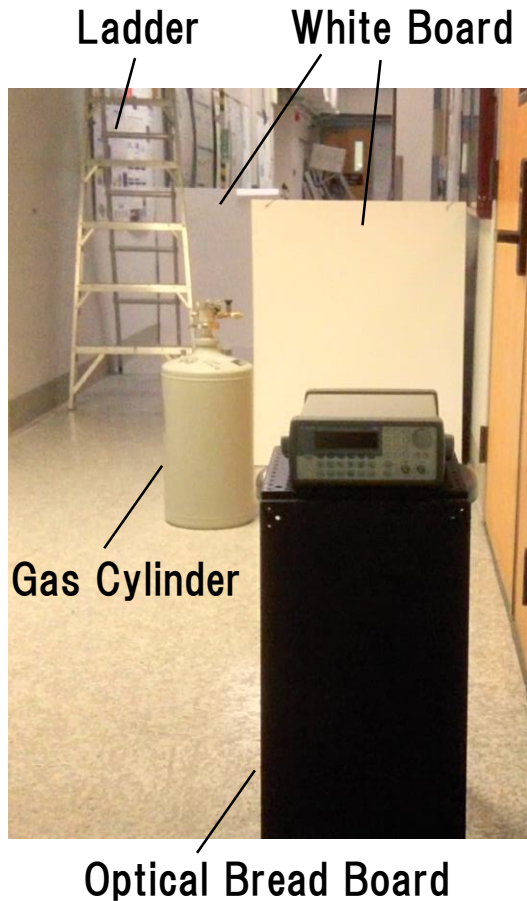


■ Measurement result

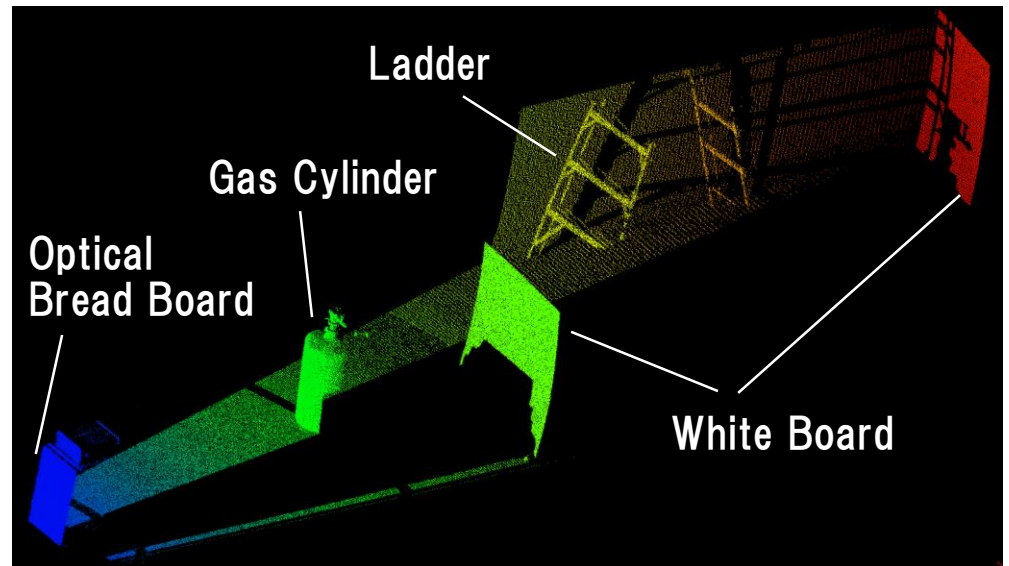
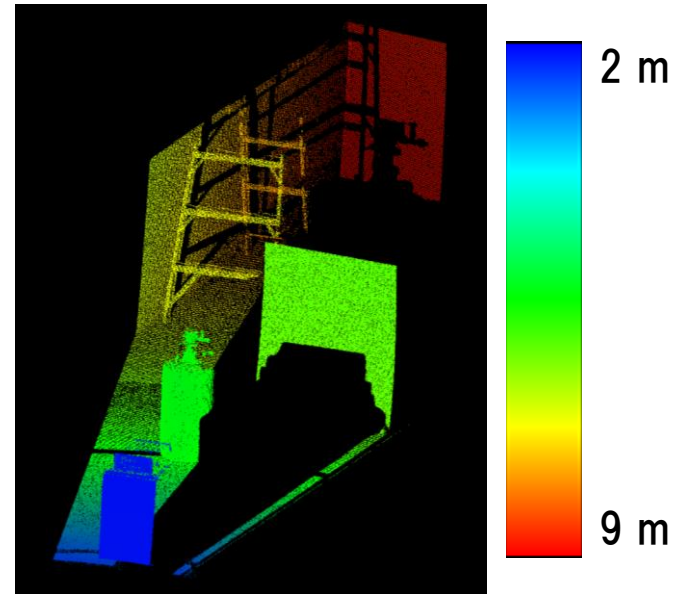


3D Imaging - Large Size -

■ Target



■ Measurement result



Distance from scanner: 2~9 m
Data points: 450×600 points

- We developed Low-Cost VCSEL FMCW System which uses re-sampling method.
- VCSEL FMCW measurement results show the accuracy is better than $10\mu\text{m}(\sigma)$ at -80dB sensitivity and $1\mu\text{m}(\sigma)$ accuracy at -60dB sensitivity. Its measurable distance is 9 m.
- We demonstrated 3D imaging from small to large size objects.
- In the future, we will integrate FMCW compact system for industrial applications.

HITACHI
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